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Revise Inc began a highly successful engineering rework service for prototying and trimming of integrated circuits with it's Silicon Editor TM instrument. The Silicon Editor TM utilizes a low power solid-state laser and is designed for precise fine-line operations on 2-D VLSI. there has been very significant activity in adjustment of prototypes,tfor example, through customization of layer thicknesses, addition of layers, experimental in situ variation of mechanical structures, device release, and machining of the substrate bulk under surface micromachined structures. The laser processes also assists in the interconnection and packaging issues for MEMS.

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FINAL TECHNICAL REPORT

(SBIR) Laser Microchemical Processing Instrument

Contract F49620-93-C-0008

Period: 15 January 1993 - 1 September 1995

Prepared for
Air Force Office of Scientific Research
Building 410
Bolling AFB DC 20332-6448

By Revise Inc.
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Concord, MA 01742

Summary

This program developed a prototype commercial laser microchemical instrument. This new machine was given the commercial name the SiliconEditor™, in keeping with it's function as a tool to modify microelectronic devices during design and testing phases of development. The prototype was then used to confirm the machine design and as a platform to apply the laser microchemical technology to microelectronic device fabrication and testing.

Revise Inc. is currently supplying it's SiliconEditor™ to commercial customers and is performing Government and commercial contract R & D in the area of the laser microchemical technology. The SiliconEditor™ was designed to meet the expectations of the demanding IC failure analysis market, which expects highly automated, user-friendly instruments in the manner of focused ion beams and e-beam testers. The SiliconEditor™ is currently available for pulsed-laser circuit modifications and laser deposition. The IC prototyping service operation has been functioning in a highly successful fashion for 12 months time. Revise has also been highly successful in live trimming and has developed a successful protocol with a leading Corporate development team of MEMS gyroscopes. This last collaboration has resulted in laser live trimming being incorporated into the manufacturing protocol of the team. The SiliconEditor™ is the first commercial product for Revise, but has already resulted in commercial system sales with deliveries in early 1995. The program is now successfully completed and has accomplished all of it's goals and commitments.

The lead engineer in the project was Dr. James Overbeck, who created the overall system design for the SiliconEditorTM and also did the detailed engineering of the mechanical parts and electronics. The report which follows describes the function of the SiliconEditor™ from a users perspective. The program has not produced any technical publications meeting speeches, or been connected with the granting of technical degrees.

There have been a large number of highly important collaborative interactions between the user center and large microelectronics companies.

Laser Microchemical Instrument Protoype

Many of the optical, mechanical and software modules from the SiliconEditor^{TM} described in Appendix I. The SiliconEditor^{TM} was engineered with great care to be compatible with the ease of use and automation expected in the integrated circuit CAD and silicon debug environments. It has a compact footprint of only 35 x 46 x 51 inches but provides 0.15-µm-resolution three-axis closed-loop-servo positioning, automatic cell and vacuum, real-time laser control of both pulse rate and pulse length, and graphical user interface with auto focus, auto level and EtherNet connection to computer-aided verification (CAV) environments.

System softwareallows manual operation from the graphical user interface. All manual stage motions are specified from point and click operations. All vacuum system and loading operations and all imaging operations including zooming and objective changes, illumination, and electronic enhancements of the digital image are also via the graphical user interface. In the manual mode laser operations are specified by "painting" on the digital image, then activated using presets on pull-down menus.

Prototyping Service Center

In November 1993, Revise Inc. began a highly successful engineering rework service for prototying and trimming of integrated circuits with it's SiliconEditor^{TM} instrument. The SiliconEditor^{TM} utilizes a low power solid-state laser and is designed for precise fine-line operations on 2-D VLSI. Table 2 collects some recent users. There has beern very significant activity in adjustment of prototypes, for example, through customization of layer thicknesses, addition of layers, experimental *in situ* variation of mechanical structures, device release, and machining of the substrate bulk under surface micromachined structures. The laser processes also assists in the interconnection and packaging issues for MEMS. Revise has already provided essential support to Rockwell and Draper Laboratory in device trimming. This last latter application has resulted in a considerable volume of parts and the Revise laser process has recently been incorporated as a manufacturing step in the planned pilot-plant volume production of devices by Rockwell.

Table 1: Recent Users of Laser Direct Write Services at Revise Inc.

Rockwell International
Draper Laboratories
Analog Devices
Cray Research
AMD
Intel
Materials Research Laboratory

Revise has a unique proprietary process capability, including the ability for maskless dry deposition of 24 different metals and semiconductors. It is the only domestic supplier of this technology and has already achieved outstanding examples of critical applications for its customers.

The Service Center has make available both etching and deposition processes for IC and MEMS developers. Revise assist users in data translation and in implementation of *in situ* test protocols. Users have the options of either forwarding parts by mail service or of delivering their parts and actively participating in real-time processing. Express mail service can be efficient and cost effective. However, many-months experimentation can be circumvented with a single *in situ* testing session with the designer present.

Technology

The laser 3-D approach makes use of fast microchemical deposition and etching, combined with a digitally addressable scanner and computer-aided-design/computer-aided-manufacturing (CAD/CAM) software. The idea of interfacing 3-D CAD/CAM software to a laser scanning tool follows recent demonstrations of rapid prototyping of macroscopic plastic parts by solution polymerization (frequently termed Stereolithography).

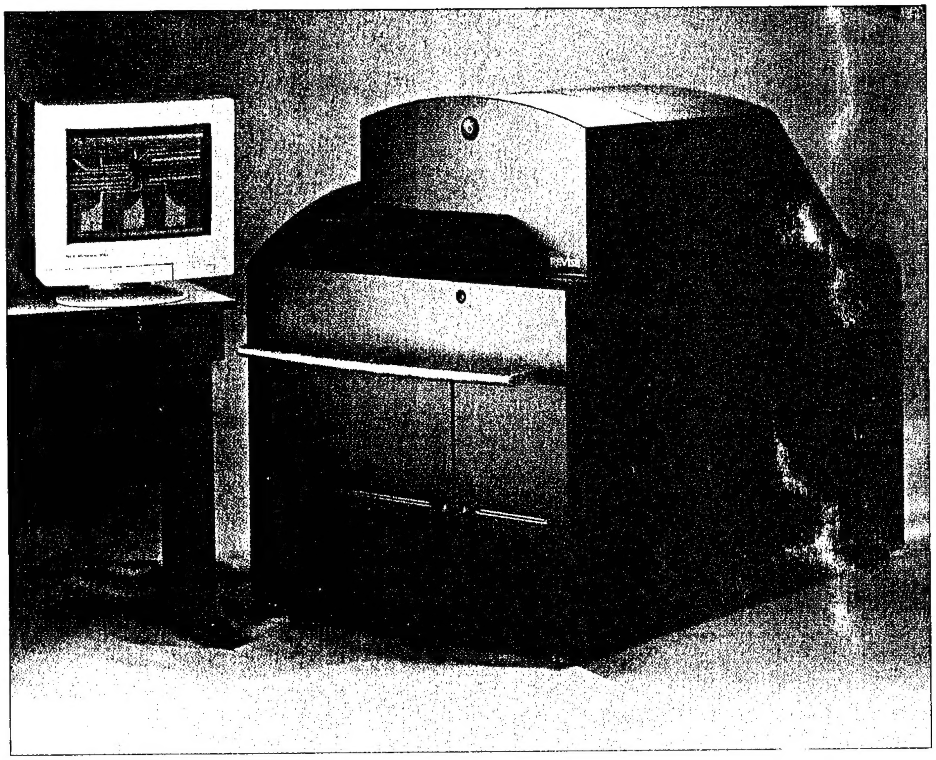
In order to obtain the required degrees of dimensional control and surface cleanliness, the microchemical technique makes use of precision laser reactions. Deposition is by local laser Chemical Vapor Deposition (CVD). For etching the thermal microreactions of silicon in a chlorine ambient are chosen because of their speed. The chlorine ambient reacts with the silicon at temperatures near the melting point to form volatile silicon chlorides, which are pumped away from the surface. The laser thermal interaction is nonablative therefore it is clean and minimally perturbing to the substrate. A removal rate of 500,000 cubic micrometers per second and a surface finish of better than 20-nm mean surface roughness have been demonstrated.

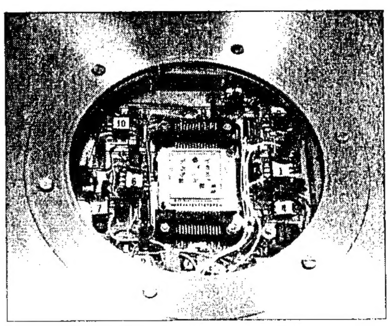
Many of the key discoveries underpinning the laser microchemical technology were made in the early 1980's under AFOSR support, by the MIT Lincoln Laboratory group consisting of Dr. Daniel Ehrlich, Dr. Richard Osgood (now at Columbia University) and Dr. Thomas Deutsch (now at the Massachusetts General Hospital). Revise has greatly expanded the control and capability of the original processes through sophisticated instrument design and is the first to commercialize the technology.

SiliconEditor™

The first system designed from the ground up to implement laser microchemical direct writing features:

- ❑ One-step, interactive modification of IC's, MCM's and MEM's
- ❑ Interconnects of millimeter length and micrometer thickness in seconds
- ❑ 3-dimensional contouring and metrology; high-speed 3-D etching





MEM device under in situ trim

CAD, CAV, Inspection and Test Interfaces

The SiliconEditor™ accepts external commands via EtherNet. Data from CAD and inspection machines can be received through this port to drive stage motions and instruct laser operation. Computer-aided verification software is offered as an optional navigational aid. Traveling optical head architecture permits in situ trim or modification under live device test.

Specifications

Deposition

Materials:	Al, Pt, W, Si, Mo, Au, Cu, Co and others at user option
Resistivity:	3-15 micro-ohm-cm (typical); <0.1 ohm per square @ 1.5 µm thick
Writing Rate:	>100 µm/s
Line Width:	Adjustable, 0.2 - 40 µm

Etching

Process:	Controlled ambient/chemical assist
Rate:	>400 μm^3/s oxide depassivation; >10^6 μm^3/s silicon 3-D

Positioning Resolution 0.15 µm (X-Y) over 6 inches, 0.10 µm (Z) over 8 mm, 14-inch wide cast steel crossed-roller-bearing stage, 3-D closed-loop servo

Substrate Up to 200 mm diameter

Load Time Less than 1 minute (automated cell)

Viewing System Color high-resolution digital microscopy, frame grabber, continuous zoom over 60x magnification range, actuated lens changer, auto-illuminator, auto-focus, auto-level

Control System Graphical user interface, mouse-driven on digitized image, recall and repeat features, real-time laser control, screen-controlled vacuum, 3-D metrology and contouring features, Microsoft Windows 3.1, EtherNet, computer-aided navigational software

Total Footprint 35 x 46 x 51 inches

Laser Diode-pumped solid state (argon-ion optional)

Facilities Requirements 120 volts (50/60 Hz), compressed air or nitrogen, 50 cfm ventilation

REVISE INC.

Detailed Instrument Design

The workpiece is viewed by a color CCD camera with RGB output. This provides a display integrated with Microsoft Windows™ and provides both real time display and display of stored ("grabbed") images. The frame grabber cannot, however, grab and display successive TV frames. The frame grabbing capability is used for automatic focusing and alignment of the laser beam to the workpiece.

The specifications of the above components are as follows:

RGB Color Camera:
- single "2/3 inch" (6.6 by 8.8 millimeter) CCD sensor
- Effective number of pixels: 768(H) x 493(V)
- Horizontal resolution = 470 TV lines
- Signal format: NTSC, 525 lines, 2:1 interlaced

Color Frame Grabber:
- 1024 by 1024 by 16 bit frame buffer
- Integrated with Super-VGA card so that computer output may be overlaid on live video

Monitor:
- 17" diagonal display, non-interlaced, 1024 x 768 pixels, 0.28 millimeter dot pitch

The camera views the workpiece through either the "cutting objective" or the "finishing objective" and through a motorized zoom lens which provides a 6.5:1 range of variation in magnification. Note however, that in this version of the SiliconEtcher, space is being reserved for infrared detectors and an infrared-sensitive CCTV camera. Use of these additional components may force the elimination of the zoom lens and replacement of it by a fixed magnification lens.

The fields of view provided as a result of the zoom capability are:

With the "finishing objective": 0.768 by 1.048 millimeters zooming to 0.1222 by 0.1630 millimeters.

With the "cutting objective": 2.829 by 3.771 millimeters zooming to 0.4400 by 0.5867 millimeters.

When the laser is hitting the workpiece laser light is blocked from entering the color camera by a Schott OG550 long wavelength pass filter. When this filter is in place all color discrimination is effectively lost and the workpiece appears orange. The purpose of this filter is to prevent possible damage to the sensor in the camera from excessive laser light.

Illumination for viewing is provided by a tungsten halogen lamp. A typical lamp lifetime is 500 hours at full intensity or as much as 10,000 hours at low intensity. The lamp output power is under computer control. Light from the illuminator is transported to the viewing optics by a fiber light pipe, so accessibility for changing lamps is not impaired.

The viewing system includes a diode laser-based fiducial generator. This generator projects a point of light onto the TV camera's sensor. The position of this point is fixed relative to the position of the focused laser beam and a manual adjustment is provided for making the two points of light coincident. The purpose of the fiducial is to compensate for the fact that the motion of the zoom lens is not perfect, due to the finite mechanical tolerances in its mechanism. As the zoom lens moves the position of the focused laser beam will appear to move, and this motion will not be repeatable. Compensation for the imperfection in the zoom lens is done by analyzing a small portion of the grabbed image after moving the zoom lens and finding the precise position of the fiducial mark in that image.

The viewing resolution is not dominated by the capabilities of the camera, frame grabber, or monitor, but by the fundamental diffraction limit of an optical system with an

F number of 2 (i.e., numerical aperture of 0.24). The spatial resolution implied by this is approximately the spot size as given in the section on the laser specifications. This is true because the viewing wavelengths and the laser wavelengths are comparable, and because laser and viewing system share the most critical optical components, the "finishing" and "cutting" objectives.

Focusing

The objective lenses travel on a vertical crossed-roller slide, so that the laser beam and the viewing system can be put in focus at any height between 1 millimeter and 9 millimeters below the bottom surface of the cell's lid. This slide is under computer control, and for position feedback it uses a linear encoder and interpolating and digitizing electronics. This combination has 0.5 micron resolution and ±0.5 micron accuracy.

Focusing is performed by analyzing a small portion of the frame grabber image which contains a surface feature having significant contrast. The image of the feature is convolved with the derivative of the line spread function of the viewing optics. The focus height at which the magnitude of this convolution integral is a maximum is judged to be the height of best focus. Examples of features with sufficient contrast are:

A. the edge of an etched hole,

B. the edge of a die (as viewed from the back side of the die.)

C. the glowing area of molten silicon produced by the ion laser beam. (Note that this has not yet been tested.)

D. the focused spot from the ion laser when the beam is highly attenuated.

E. the focused spot from a diode laser module located in the area reserved for end point detection using light induced photocurrents. (The end point detection equipment is not available at present, so a standard laser diode module is provided until the end point detection equipment is available.) This diode laser provides a laser spot which can be made available quickly, i.e., without taking the time to attenuate the ion laser beam.

An optical system has the value of its convolution integral fall to 0.707 times its maximum value for a defocus equal to (4/p) times the median wavelength times the square of the F number. In this case this product is 2.8 microns. This assumes a perfectly sharp, infinite contrast surface feature. In cases where the signal to noise ratio is good one can reliably detect reductions of less than 10% in the value of the convolution integral.

Computer

The computer used to control the SiliconEtcher will be an IBM-PC-AT-compatible computer with the following capabilities (or better):

Intel 50 MHz 486DX CPU
8 Megabytes DRAM
250 Megabyte 13 millisecond Hard Disk
3.5" and 5.25" Floppy Disks
124 Key Keyboard
Microsoft Mouse
Microsoft Windows™ and MS-DOS software

The computer also holds the following cards for control of the SiliconEtcher:

An EtherNet card for communication with the Sparc 10 which runs the navigation software
A 330 KHz 16 channel, 12 bit analog input board
A color frame grabber board
A four axis dedicated servo controller

Machine Control Software Capabilities

The following describes the direct machine interface software controls. Data-base and MEMS design and test software interfaces are constitute a separate program element and described elsewhere in this document.

Software controls:

vertical motion of objective lenses
switching between "finishing" and cutting" objective lenses
switching electro-optic modulator in and out of laser beam path
transmission of electro-optic modulator
laser plasma tube current
xy position of cell
xy position of galvanometers
gas and vacuum connections to the cell
intensity of viewing illumination
intensity of fiducial spot
zoom magnification

Sensing of:

Focus and alignment through grabbing and analysis of TV images
Cell pressure and temperature
Outgoing and reflected laser power
Interlock status

Information interface capabilities:

Acceptance of xy coordinates and etch geometry from navigation software (via Ethernet), from a text file, or from the operator's positioning a cursor on a video image

Provision for user modification of these coordinates, i.e., arbitrary coordinate transformations

Acceptance of process specifications such as cell pressure, scanning speed, and laser power from a text file or from the operator's selections in a Windows™dialog box.

Both "high" and "low" levels of machine control are provided. The "graphic user interface" operates under the Windows™ 3.1 system and follows the IBM style guidelines.

The use of windows overlying real time (or stored) video, and other aspects of the style of user control over the machine via the graphic user interface are similar to those demonstrated on the Revise SiliconEditor™.

Graphical User Interface

The SiliconEtcher is controlled through a well developed graphical user interface which operates under MS Windows 3.1. The following features are provided:

Digitized Video image

All operations are specified by painting operations on the image or through windows generated through pull-down menus on a single terminal. Optional Knight's Technology navigational software operates remotely on a separate work station.

Viewing Window

This window provides all the controls for viewing including, objective choice, zoom magnification, focus and illumination intensity. CCD camera settings , electronic (nonoptical) zoom, and frame-grabber adjustments are not directly accessible from this window but are completely adjustable from a more protected software control.

Manual Navigation

The SiliconEtcher can be manually navigated with a "map" control that provides rapid global positioning and, also, by point-and-click panning specified on the video image. Navigation is truly three dimensional. Locations specified as x,y,z coordinate data can be stored and retrieved as locations of interest or as laser process destinations.

Manual Operate Window

The laser operate window allows custom laser operations using presets or operator-set laser and stage motion conditions. Typical presets are known optimum cutting conditions for specific substrates. Laser trajectories on the substrate are specified by point-and-click painting operations on the video image.

Experiment Controls

Software is provided for systematic stepwise variations of laser and scan conditions. This feature is used for rapid semiautomatic determination of best laser process conditions.

Cell Mechanical Interface

The interior of the cell is 6.5 inches in diameter and 0.75 inches high. Four 6-32 UNC-2B blind tapped holes in a 3.875 inch square pattern are provided in the bottom of the cell for attachment of fixturing. This is shown in the Cell Mechanical Interface Drawing, Figure 4. The system will be capable of handling 4" and 6"-diameter silicon wafers and piece parts in both packaged and unpackaged form. Part holders for packaged parts are most elaborate since they will permit in situ electronic excitation of MEMS prototypes for real-time trimming and parametric experimentation. Two representative fixtures shown in figures below are:

A. A fixture holding a Textool 2-0625 "Grid ZIP" 625 pin zero insertion force socket for pin grid array packages, shown in Figure 5.

B. A fixture for holding inverted pin grid array packages, shown in Figure 6.

The surface being etched must be located between 1 and 9 millimeters below the bottom surface of the cell's lid, i.e., below the top of the 0.75 inch deep volume. The area being etched must be located within a 30 millimeter diameter circle which is concentric with the cell.

In the center of the bottom of the cell is a 3.25 inch diameter hole. Below this hole is a blank stainless steel plate, 4 inches in diameter by 0.25 inches thick. There is an o-ring groove in this plate for sealing it to the bottom of the cell. This plate is intended to be modified by the user for such purposes as bringing electrical connections into the cell. It is the user's responsibility that the modifications to this plate are safe, are resistant to chlorine, and are vacuum tight. The program will develop fixtures according to user demand as outlined in section 3 below.

XY Motion

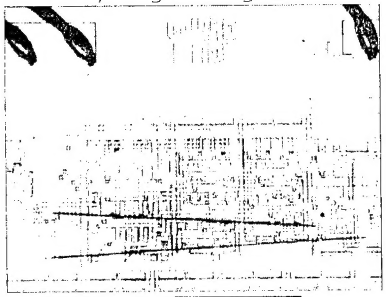
XY motion from one etch site to another over a minimum of a 4-inch diameter area which is accessible through the cell's window. During loading and unloading

operations the y range of travel is increased to approximately 8 inches. The motion system includes an Anorad "Anoride 14" xy stage similar to that used for moving the optics package in the SiliconEditor^{TM}. It features glass linear encoders with 0.078 micron resolution, linear motors, crossed roller bearings, and well controlled preload on the bearings.

The specifications, which apply over a 1.5 inch square area are:
3 sigma repeatability = ±1 micron from target position
straightness = ±1.7 microns from best straight line over 4 inches
flatness of motion = ±2 microns deviation from average over 4 inches
and ±0.83 microns over 12 millimeters
orthogonality = ±10 arc seconds
3 sigma accuracy = ±3 microns (dead reckoning)

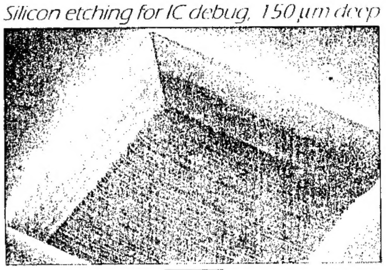
Note that edge placement is supplemented to submicron accuracy by image-based pattern recognition. This is a superior approach over improving the dead reckoning capability of the stage since thermal expansion changes during laser thermal processing are more easily compensated with an image-based approach.

Rework of packaged analog circuit



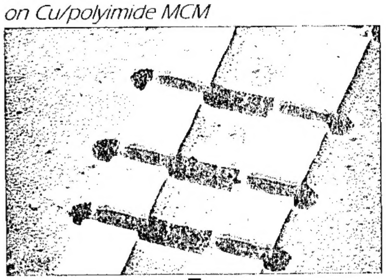
1.5 mm

Silicon etching for IC debug, 150 µm deep



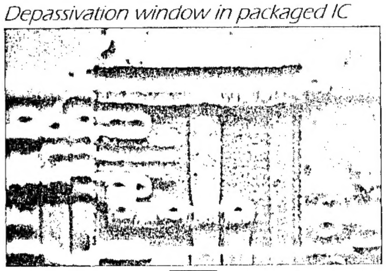
100 µm

Controlled-ambient cuts on Cu/polyimide MCM



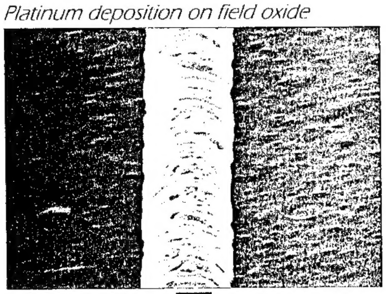
10 µm

Depassivation window in packaged IC



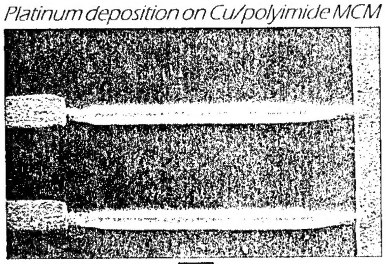
10 µm

Platinum deposition on field oxide



1 µm

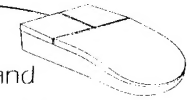
Platinum deposition on Cu/polyimide MCM



100 µm

Product Features

Interactive Graphical User Interface



The SiliconEditor™ menu-driven graphical user interface (GUI) displays a live video image of the workpiece. Motions and editing operations are specified by point-and-click operations on the image. Paths are specified as arbitrary multi-line segments in X, Y and Z. The system can contour up steps and over steep topographical features. All vacuum, load, viewing and laser operation options are controlled through macros specified by clicks on the pull-down menus.

Automation and Throughput

Fully actuated pneumatic cell. Save-and-repeat features for duplication of editing operations on multiple substrates.

Superior Nondestructive Imaging

High-magnification color digital optical microscopy, actuated two-objective viewing system and motorized zoom, scanned through a 60-fold magnification range. Further magnification and image processing through electronic manipulation of the digitized color image.

Submicrometer Metrology Over 6-Inch Travel

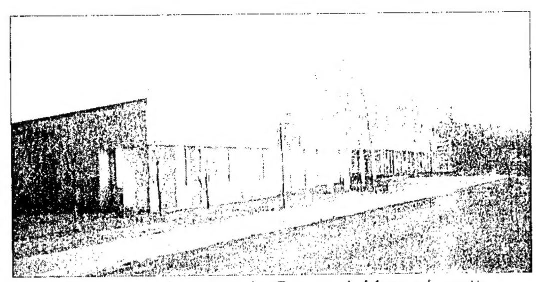
Reads and displays absolute position and calculates distance between specified positions.

World-Class Laser Microchemical Technology

The MIT laser deposition processes write metal typically to within a factor of two of bulk conductivity. Processes are available for 21 different metals, semiconductors and dielectrics. Metal thicknesses greater than 10 µm are easily obtained in MCM configurations. Line widths as small as 0.2 µm can be achieved for VLSI. Controlled-ambient laser etching permits high material selectivity with minimum damage to underlying layers.

Technology Commitment

Revise has leveraged 40 man-years of MIT laser direct write technology through licenses to the key process patents. A SiliconEditor™ installed at our facility enables real-time hands-on customer evaluations. Revise personnel provide expert process development assistance. Laser direct write services are available on a contract basis.



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